Spectral Modeling of Sub-Mesoscale Mixing Processes in the Ocean

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LONG-TERM GOALS

The main long-term goal of the project is two-fold: to further develop a new venue in modeling of turbulent mixing using a new spectral theory of turbulence, the quasi-normal scale elimination (QNSE), and to improve the nowcasts and forecasts of the state of the ocean on sub-meso- and meso-scales. The QNSE theory brings turbulence modeling to a new level as it allows one to obtain analytical results in situations not amenable to analytical treatment within the Reynolds stress closure modeling approach. The QNSE theory is particularly useful in describing anisotropic turbulence with waves, the flows of central importance to oceanic and atmospheric circulations. We consider this theory as a viable alternative to the Reynolds stress modeling and we expect it to find a wide range of applications in the long range.

OBJECTIVES

Project objectives include further development of the QNSE model, using the results to gain better understanding of important physical processes on both small and large scales, and porting the theoretical results into numerical schemes in order to improve these schemes. Due to the similarity between certain processes, our research covers both large- and small-scale turbulence. These phenomena include anisotropic turbulence and waves and can be treated under the umbrella of a unified theory. Progress in one area can be beneficial to the other area and much can be learned from the inter-comparisons between diverse areas. A good example of this approach is the exploration of the similarity between internal gravity and Rossby waves described below.

APPROACH

The project objectives entail coordinated theoretical and numerical components. The theoretical component is built upon the QNSE theory. This model employs successive small scale elimination and allows one to readily introduce into consideration such parameters as the grid resolution, degree of anisotropy, spectral characteristics, etc. Applied to anisotropic turbulent flows with waves, the method shows how turbulence modified waves and enables one to derive analytically various one-dimensional and three-dimensional spectra. When all turbulent scales are eliminated, the QNSE theory recovers the Reynolds-averaged, Navier-Stokes (RANS) based models. However, relying upon more comprehensive physical background than the RANS models, the QNSE method produces results that often turn out to be superior to RANS. Our research also includes direct numerical simulations of the barotropic vorticity equation on a beta-plane. These studies are geared towards elucidation of the

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14. ABSTRACT
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15. SUBJECT TERMS

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physics of quasi-two-dimensional turbulence with the inverse energy cascade and Rossby waves. Not only this area is related to the large-scale planetary circulations and is important on its own sake, but strong turbulence anisotropy and the effect of Rossby waves make this phenomenon very useful for inter-comparisons with stably stratified turbulence.

WORK COMPLETED

We have completed tasks 1. Preliminary explorations with QNSE-based RANS models; Task 4. Implementation of the QNSE model in RANS mode, and Task 5. 1D simulations with QNSE-based RANS models. Task 6. Dissemination of the results is partially completed, and Task 2. Extension of the QNSE model to rotating flows, and Task 3. Extension of the QNSE model to rotating and stably stratified flows are ongoing.

RESULTS

One of the important results of this project is the revision of the issue of the critical Richardson number, Ri_{cr}. According to widely accepted definitions, this parameter characterizes the strength of stable stratification at which turbulence undergoes laminarization. This parameter plays an important role in oceanography, meteorology, planetary science and astrophysics. Using the data and QNSE theory, we have revised the notion of Ri_{cr} and shown that stable stratification causes turbulence anisotropization and enhancement of the horizontal mixing along with the suppression of the vertical mixing. In addition, the vertical turbulent momentum mixing can never be completely suppressed. Our conclusion was that Ri_{cr} simply does not exist! This work was described in Galperin et al. (2007).

We have performed numerous simulations of small-scale forced two-dimensional turbulence on the surface of a rotating sphere. We have investigated turbulence anisotropization under the action of the beta-effect and the interaction between turbulence and Rossby waves. We have discovered a new flow regime which was coined zonostrophic turbulence. Then we have found a new class of nonlinear waves in zonostrophic turbulence and coined them zonons (Sukoriansky et al., 2008). These zonons appear like westward moving eddy with the phase speed of the most energetic Rossby waves. We have found an analogy between the wave number of the threshold of flow anisotropization on beta-plane, k_β, and the Ozmidov wave number characterizing the threshold of anisotropization in stably stratified flows, $k_O = (N^3/\varepsilon)^{1/2}$. We have also found analogies between scalar mixing on the beta-plane and in stably stratified turbulence.

One of the important results is the analytical derivation of the vertical shear spectrum.
Using the QNSE theory, we have developed an analytical expression for the vertical spectrum of the horizontal velocity in the case of weak stratification,

$$E_1(k_3) = 0.626\, \varepsilon^{2/3}\, k_3^{-5/3} + 0.214\, N^2\, k_3^{-3}, \qquad (1)$$

where ε is the rate of the viscous dissipation and N is the Brunt-Vaisala frequency.
Based upon a series of measurements in the oceanic mixed layer, Gargett et al. (1981) suggested a universal scaling of the vertical shear,

$$E_S\,(x)/E_B = F(x), \qquad x \equiv k_3/k_O, \qquad (2)$$

where $E_B = (\varepsilon N)^{1/2}$ and F(x) is a nondimensional function and $k_O = (N^3/\varepsilon)^{1/2}$ is the Ozmidov wave number. Gargett et al. (1981) commented that ``in the intermediate-wavenumber range... the collapse of the observations to a single curve [F(x)] over the range $0.1 < k_3/k_O < 1$ is remarkable..." Later, this scaling was verified by Gregg et al. (1993) using several different data sets. These authors noticed that ``Gargett et al. (1981) are uncertain whether the spectral collapse effected by their buoyancy scaling demonstrates the existence of the Shur-Lumley buoyancy subrange or whether it is simply fortuitous... The buoyancy scaling used by Gargett et al. (1981) does collapse their observations... the same scaling is applied to PATCHEX and PATCHEX north... The results are dramatic, achieving a better collapse than obtained by Gargett et al. The collapse extends across the internal wave range... If this collapse is not also fortuitous, the scaling must represent internal wave dynamics rather than buoyancy-modified turbulence..." It is apparent that despite the extensive observational basis of the scaling (2), the questions of its validity and physical nature, as well as the existence and the analytical form of the function F(x) remain unanswered.

One can use (1) to derive an equation for the normalized vertical shear spectrum,

$$E_S(k_3/k_O)/E_B = 2\, k_3^2\, E_1(k_3)/\, (\varepsilon\, N)^{1/2} = F(k_3/k_O)$$
$$= 1.252\, (k_3/k_O)^{1/3}\, [\, 1 + 0.34\, (k_3/k_O)^{-4/3}]. \qquad (3)$$

This equation provides an analytical expression for the function F(x) in (1) (the coefficient 2 in the second expression on the left is stipulated by E_S being the sum of two horizontal components). Equation (3) thus asserts that the scaling (2) is not `fortuitous;' on the contrary it complies with the fundamental scaling of stably stratified turbulence developed in Sukoriansky and Galperin (2005).

Figure 1 compares Eq. (3) with the observational data by Gregg et al. (1993). All data points collapse well on one line for $k_3/k_O < 1$.

The QNSE model has been implemented in the state-of-the-art atmospheric model WRF being developed and maintained at NCAR. The model was tested in a simplified one-dimensional formulation for the case of stable stratification. The implementation included three elements: the surface fluxes parameterization based upon the QNSE-derived Monin-Obukhov stability functions and drag coefficients; the QNSE-based vertical profiles of the eddy viscosity and eddy diffusivity, and the turbulence macroscale formulation that ensures a smooth transition from the Blackadar to a stratification- determined value.

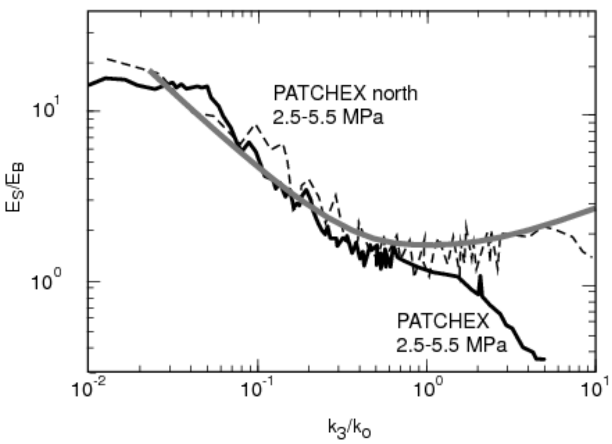
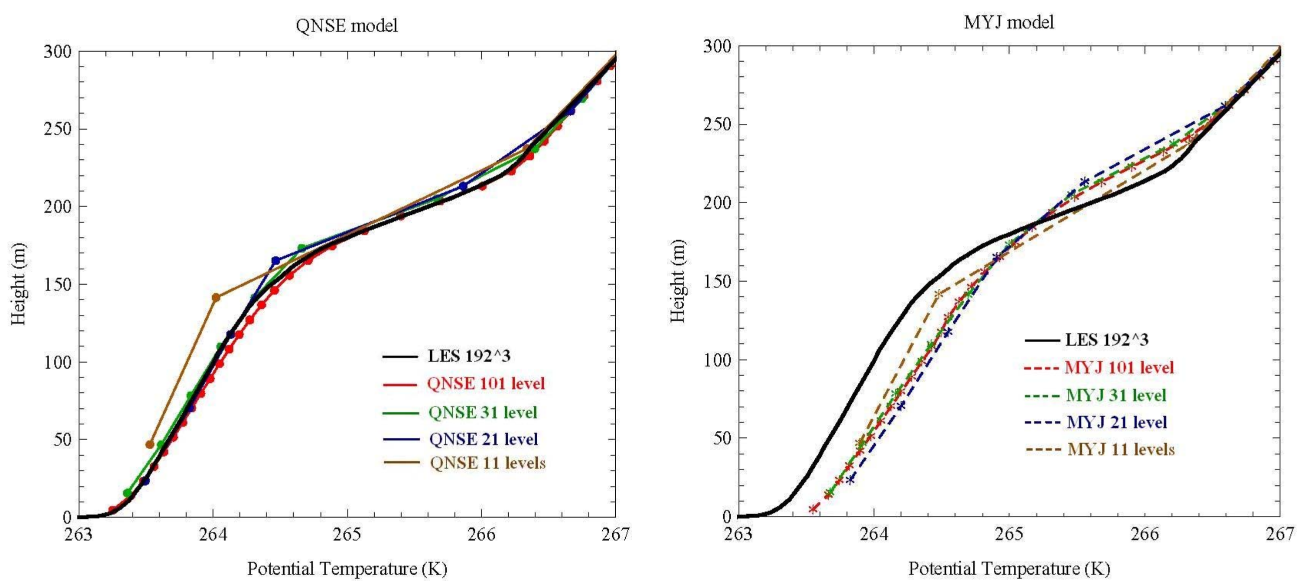


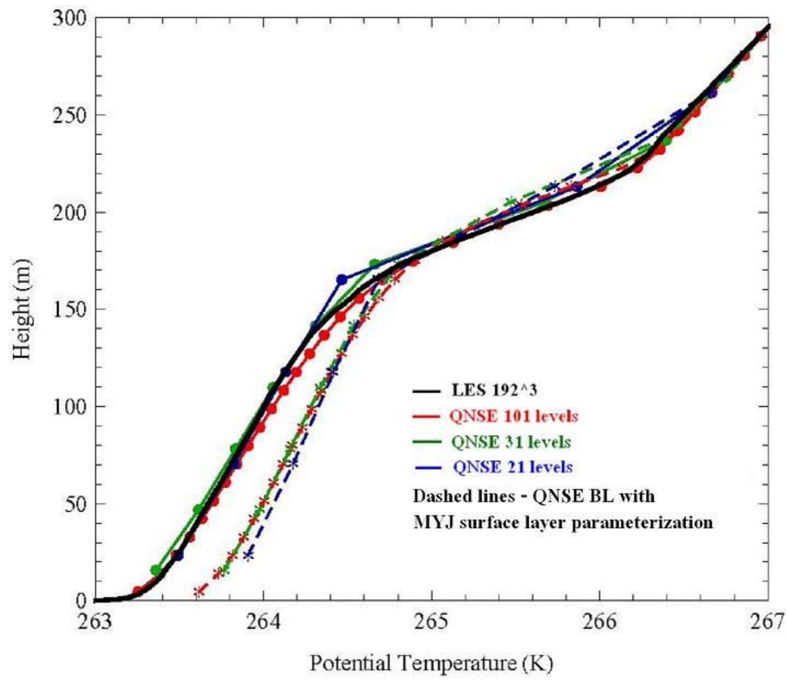
Figure 1. The vertical shear spectrum as measured in the PATCHEX and PATCHEX north experiments (Gregg et al. (1993)) and predicted by the QNSE theory, Eq. (3), gray line.

The 1D version of QNSE WRF has been tested against LES of the BASE campaign with different resolutions and found to produce robust results even with very crude resolution. Note that even in case of moderate stable stratification, LES requires grid resolution of about 2m for reliable reproduction of data. At cruder resolutions, the quality of simulations rapidly degrades (Bear 2004). The QNSE scheme, on the other hand, provides satisfactory performance at much cruder resolutions. The figure below compares the results obtained with WRF employing the QNSE (left panel) and Mellor-Yamada-Janjic (MYJ) (right panel) models with different resolutions with LES by Stroll and Porte-Agel (2008) with their highest resolution of 192^3. Very similar results were obtained in the high-resolution LES by Beare and MacVean (2004).



One can see that, firstly, the QNSE results are in very good agreement with LES for all resolutions except the case with 11 vertical levels when the first level was at 50m; secondly, the MYJ model could not replicate the BASE data for any resolution.

Another test was designed to investigate the importance of the QNSE-based surface layer parameterization. The figure below compares results of simulations with the QNSE-based eddy viscosity and eddy diffusivity with the QNSE- and MYJ-based surface layer parameterizations. It is easy to see that while the QNSE-based results are in excellent agreement with LES, the MYJ-based surface layer parameterization yields poor performance highlighted by a significant warm bias in the near-surface temperature.



Currently, the QNSE scheme is being tested in WRF. The QNSE physics option will be available in the new release of WRF planned for March 2009.

IMPACT/APPLICATIONS

Exploring the analogies between various turbulent flows that support linear waves and develop strong anisotropy will greatly contribute to our understanding of these flows and improving the ability to model them. Re-evaluation of the concept of the critical Richardson number may give a positive impetus to ocean modelers as the impact of Ri_{cr} has been too restrictive in many applications. The QNSE-based RANS models are a viable alternative to the Reynolds stress models and may replace them in certain applications.

RELATED PROJECTS

The QNSE model has been used for simulations of stably stratified atmospheric boundary layers in the framework of the US Army Research Office project “Advanced parameterization and modeling of turbulent atmospheric boundary layers“ (ended on August 31, 2008). In this effort, the QNSE model has been used for theoretical and numerical studies of atmospheric boundary layers. At the present, the QNSE model is being implemented in the state-of-the-art atmospheric code WRF developed at NCAR.

The QNSE model will become available to the community of WRF users as an option of the new Physics package in the new release of WRF due in March, 2009.

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